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ASTRONOMY AND ASTROPHYSICS

Hard X-ray observations of GX 339-4 with *GRANAT*/SIGMA

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Abstract. The results of hard X-ray/soft gamma-ray observations of GX 339-4 with *GRANAT*/SIGMA are reported. The spectral and temporal properties of the source during its four successive hard X-ray outbursts in $1990 - 1994$ were studied in details. We suggest that the mechanism of GX 339-4 outbursts is triggering of the irradiation – driven instability in the low mass binary system.

Key words: stars: individual: GX 339-4 – accretion, accretion disks – black hole physics – gamma-rays: observations – X-rays: stars

1. Introduction

From the previous studies at least three distinct regimes of spectral and temporal behaviour of GX 339-4 (4U $1658-486$) were established: *soft* (*high*), *hard* (*low*) and *off* states. Hard outbursts (*low* state) are known to be characterized by the hard spectrum generally described by the comptonization model and strong short term aperiodic flux variations (Grebenev et al.1993; Harmon et al.1994b; Grabelsky et al.1995). In the *high* or *soft* state typically observed at the end of hard outbursts, the standard X-ray band (1-10 keV) flux is at its maximum (Grebenev et al.1993), with a nearly black body spectrum and a relatively weak hard tail. The *off* state is characterized by undetectable or very low ($\leq$30 mCrab) X-ray flux (Markert et al.1973; Grebenev et al.1993). GINGA observations in 1988 revealed a *very high* state of the source characterized by the soft X-ray flux several times exceeding typical *high* state value and aperiodic variability properties unusual for the *soft* state (Miyamoto et al.1991).

Due to these properties resembling very much the behaviour of dynamically proven black hole binaries (Cyg X-1, several X-ray Novae) it was suggested that the binary system in GX 339-4 harbors a black hole. On the other hand the compact object mass estimates from the optical studies (Cowley, Crampton, & Hutchings 1987, Callanan et al.1992) range from $1M_{\odot}$ to $2M_{\odot}$ with the most probable value $\approx 1.4M_{\odot}$ supporting the neutron star rather than a black hole interpretation.

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2. Instrument and observations

The French coded-mask telescope SIGMA (Paul et al.1991) aboard Russian *GRANAT* orbital observatory provides an arcmin resolution sky images in the 35-1300 keV energy band divided into 95 energy channels. The instrument nominal angular resolution (corresponding to the mask pixel size) is ≈ 15 arcmin. The point source localization accuracy varies from $3-4$ arcmin to less than 1 arcmin, depending on the brightness of the source and the number of observations. Half-sensitivity boundary of field of view (FOV) is a $11.^{\circ}5 \times 10.^{\circ}9$ rectangle of which central $4.^{\circ}7 \times 4.^{\circ}3$ correspond to fully coded field of view with constant sensitivity. The energy resolution of the instrument at 511 keV is $\sim$ 8%. The typical duration of individual observation is ≈ 20 hours, providing the sensitivity (1σ) $\approx 10 - 20$ mCrab in the 35-150 keV energy domain.

GX 339-4 has been observed by SIGMA during five sets of observations in 1990-1994. During four observational periods the activity of the source in hard X-ray energy domain was detected with typical 35-150 keV flux around $\approx 200 - 400$ mCrab (Table 1).

The results of the 1990 – 1991 SIGMA observations were reported by Bouchet et al.1993. In the present paper we summarize briefly the results of the 1990 – 1991 observations, report results of the 1992 – 1994 observations and discuss the possible origin of source outbursts in the framework of the mass transfer instability model (MTI; Hameury, King, & Lasota 1986, 1988, 1990).

3. Results

3.1. 1990 observations

GX 339-4 was found in the typical *low* (*hard*) X-ray state with an average $35 - 150$ keV flux ≈ 210 mCrab during the first SIGMA observation of the source in Mar., $27 - 28$, 1990 (Table 1)(Grebenev et al.1993, Bouchet et al.1993). Approximation of

Table 1. SIGMA observations of GX 339-4 during 1990-1994

Date, UT	Exposure time (hours)[b]	Flux, mCrab[a] 35-150 keV
	1990	
Mar. 27.37 - 28.57	23.86	214 ± 12
Aug. 22.68 - 23.43	15.00	22 ± 9
	1991	
Feb. 18.43 - 19.50	21.01	19 ± 12
Feb. 19.65 - 20.65	20.00	0 ± 8
Aug. 21.39 - 22.51	16.00	400 ± 11
Aug. 29.40 - 30.49	21.52	380 ± 10
Sept. 6.60 - 7.51	18.00	430 ± 10
Sept. 28.37 - 29.24	17.16	136 ± 10
Oct. 5.39 - 6.20	16.00	47 ± 11
	1992	
Feb. 10.65 - 11.63	19.33	9 ± 9
Feb. 11.76 - 12.41	13.00	5 ± 11
Feb. 13.48 - 14.51	20.31	3 ± 12
Mar. 6.78 - 7.99	24.00	-7 ± 19
Oct. 12.49 - 13.30	16.00	207 ± 14
Oct. 13.43 - 14.28	17.00	239 ± 13
	1993	
Feb. 12.48 - 13.55	21.00	0 ± 11
Feb. 13.67 - 14.68	20.00	-10 ± 11
	1994	
Feb. 11.77 - 12.51	14.69	320 ± 17
Feb. 13.72 - 14.67	19.00	280 ± 17
Mar. 4.50 - 5.51	20.00	350 ± 16
Mar. 5.64 - 6.68	20.65	380 ± 16

[a] – 1 mCrab corresponds to $\sim 1.4 \times 10^{-4}$ photons/s/cm^2 ($\sim 1.5 \times 10^{-11}$ ergs/s/cm^2) for the 35-150 keV band (assuming the Crab-like source spectrum (α ~-2))
[b] – exposure time without dead time correction

the averaged source spectrum in the $40 - 300$ keV energy range with a comptonization model (Sunyaev & Titarchuk 1980) gives an electron temperature $kT_e \approx 31 \pm 7$ keV and a Thomson optical depth $\tau \approx 3.95 \pm 1.86$ (assuming a spherical geometry).

Two following late August observations have not revealed statistically significant flux from the GX 339-4 position in the SIGMA energy band (Table 1) (Bouchet et al.1993). According to the ART–P telescope data (Grebenev et al.1993) the source was in *high*(*soft*) state at that time.

3.2. 1991 flare observations

The beginning of this hard flare has been detected by BATSE instrument onboard the CGRO satellite (Fishman et al.1991) in July, 1991. In the middle of August the source flux ($20 - 100$ keV) has reached ≈ 400 mCrab and remained at this level up to the middle of September (Harmon et al.1994b). The SIGMA telescope performed five observations of the source between Aug. 21 and Oct.5 (Table 1)(Bouchet et al.1993).

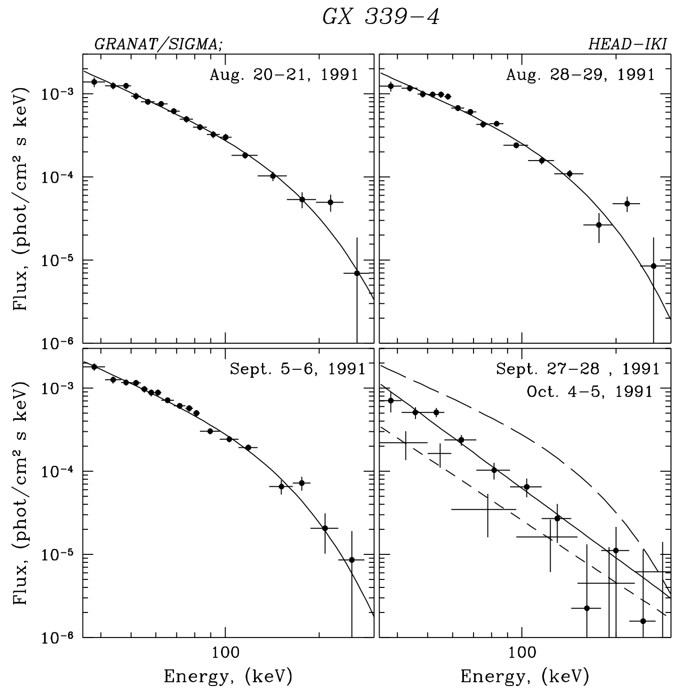

Fig. 1. The 40 – 300 keV spectra of GX 339-4 obtained by SIGMA in Fall 1991. Solid lines represent the approximation of data with a comptonization model for Aug. 20 – 21, Aug. 28 – 29, Sept 5 – 6 observations and the power law approximation for Sept. 27 – 28 and Oct. 4 – 5 observations. For comparison the comptonization model approximation for Aug. 20 – 21 observation is shown by dash–dotted line.

The evolution of GX 339-4 hard X-ray spectrum during this period can be described in terms of its steepening and gradual decrease of its intensity (Bouchet et al.1993, Harmon et al.1994b) (Fig. 1). Contrary to the hard X-ray domain, the soft X-ray flux from the source monotonically increased at the same time, indicating that the source underwent transition from the *hard* spectral state to the *soft* one (Grebenev et al.1993).

3.3. 1992 flare observations

During the February–March 1992 SIGMA and ART–P observations the source was found in the *off* state with 3σ upper limits on the average $35 - 150$ keV flux 18 mCrab (Table 1) (*see also* Grebenev et al.1993).

The source was on again during October 1992 observations. On Oct., $12 - 14$, 1992 it was detected by SIGMA in its *hard* (*low*) state with an average 35-150 keV flux ≈ 220 mCrab (Table 1). According to the *BATSE* data (Harmon et al.1994b) the lightcurve and spectral evolution of GX 339-4 in the hard X-ray – soft gamma ray ($\geq$20 keV) energy band was very similar to that of 1991, Fall flare. The average source spectrum is clearly seen up to 300 keV and its shape is well described by a comptonization model with electron temperature $kT_e \approx 40$ keV and a Thomson optical depth $\tau \approx 3.1$ or by an optically thin thermal bremsstrahlung with a characteristic temperature ≈ 160 keV in the $40 - 300$ keV energy range (Table 2, Fig. 2). It should be

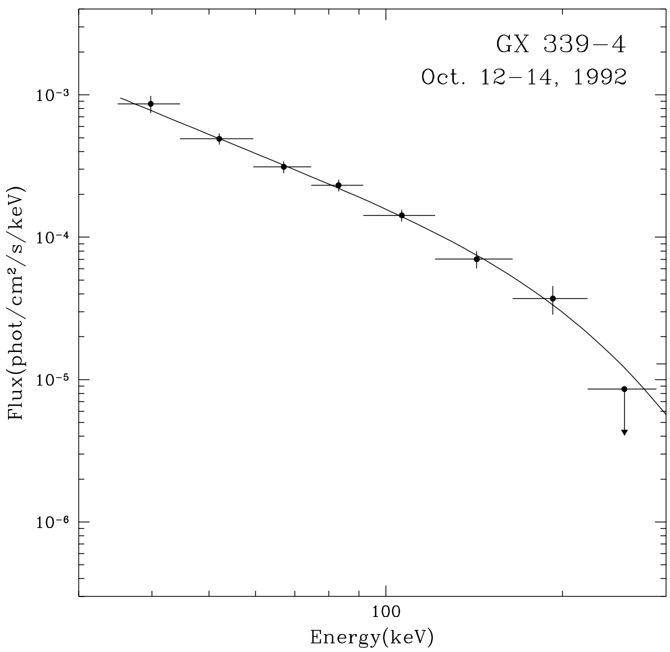

Fig. 2. The averaged 40 – 300 keV spectrum of GX 339-4 obtained by SIGMA in Fall 1992. Solid line represents the approximation of data with a comptonization model.

Table 2. The GX 339-4 spectral fit parameters in Fall, 1992 (40 – 300 keV band, SIGMA data)

Par.	Date (1992UT) Oct., 12–13	Oct., 13–14
Power law		
α	1.88 ± 0.14	2.04 ± 0.13
F_{60}^{a}	3.54 ± 0.28	3.99 ± 0.27
χ^2(dof)	50.5(45)	46.9(45)
Optically thin thermal bremsstrahlung		
T, keV	188^{+62}_{-41}	141^{+34}_{-25}
F_{60}^{a}	3.58 ± 0.27	4.06 ± 0.25
χ^2(dof)	47.9(45)	44.6(45)
Comptonization model (Sunyaev & Titarchuk,1980)		
kT_e, keV	46^{+19}_{-10}	40^{+20}_{-8}
τ	$3.11^{+1.08}_{-0.91}$	$3.18^{+1.25}_{-1.08}$
F_{60}^{a}	3.46 ± 0.26	3.97 ± 0.24
χ^2(dof)	47.1(44)	44.0(44)

^{a} – spectral flux at 60 keV, $\times 10^{-4}$ phot cm^{-2} s^{-1} keV^{-1}

noted that the source spectrum at that time was somewhat harder than usual hard state outburst spectra.

3.4. 1994 flare observations

As GX 339-4 was observed but not detected in 1993 (see Table 1), we will pass directly now to the results of the 1994 observations. GX 339-4 was the target of four SIGMA observations in February – March, 1994 (Table 1). The source has been found in the *hard* (*low*) state with spectral and temporal characteristics close to the one observed during the 1991 hard flare (Fig. 3, Table 3).

Table 3. The GX 339-4 spectral fit parameters in Spring, 1994 (40 – 300 keV band, SIGMA data)

Par.	Date (1994UT) Feb., 11–12	Feb., 13–14	Mar., 4–5	Mar., 5–6
Power law				
α	2.38 ± 0.16	2.36 ± 0.14	2.58 ± 0.12	2.53 ± 0.11
F_{60}^{a}	5.78 ± 0.42	5.14 ± 0.33	6.67 ± 0.31	7.04 ± 0.31
χ^2(dof)	33.5(45)	83.8(45)	50.9(45)	45.8(45)
Optically thin thermal bremsstrahlung				
T, keV	85 ± 18	88^{+15}_{-13}	68 ± 9	73^{+9}_{-8}
F_{60}^{a}	6.00 ± 0.45	5.38 ± 0.32	7.03 ± 0.33	7.33 ± 0.32
χ^2(dof)	31.2(45)	76.0(45)	47.8(45)	46.2(45)
Comptonization model (Sunyaev & Titarchuk,1980)				
kT_e, keV	35^{+26}_{-9}	26^{+5}_{-6}	30 ± 8	45^{+28}_{-11}
τ	$2.89^{+1.48}_{-1.24}$	$5.30^{+4.93}_{-1.86}$	$2.88^{+0.62}_{-1.27}$	$2.00^{+0.65}_{-1.20}$
F_{60}^{a}	5.93 ± 0.40	5.42 ± 0.32	6.91 ± 0.31	7.16 ± 0.31
χ^2(dof)	31.1(44)	73.4(44)	47.4(44)	44.2(44)

^{a} – spectral flux at 60 keV, $\times 10^{-4}$ phot cm^{-2} s^{-1} keV^{-1}

According to the SIGMA data the averaged hard X-ray spectrum has parameters very close to that measured during previous observations of hard X-ray outbursts; the best fit parameters of comptonized spectrum are $kT_e \approx 33 \pm 4$ keV, $\tau \approx 2.95 \pm 0.50$ (assuming a spherical geometry).

4. Discussion

According to BATSE results, three successive hard X-ray outbursts of GX 339-4 with $\approx 440 \pm 30$ days cycle duration occurred during $1991 - 1994$ (Fishman et al.1991; Harmon et al.1992; Harmon et al.1994a). It was pointed out that the spectral and temporal properties of the source are very similar for these outbursts (Harmon et al.1994b), which is fully consistent with the results of SIGMA observations.

4.1. Hard X-ray spectral evolution during the outbursts

In Fig. 4 (*middle panel*), the best-fit bremsstrahlung temperature is shown as a function of time since the start of the outbursts for the 1991, 1992, 1994 SIGMA observations (all SIGMA observations when the statistically significant flux from GX 339-4 was detected) The outbursts start times were taken from the (Harmon et al.1994a, Harmon et al.1994b). The upper panel in Fig. 4 shows the 40–300 keV flux from the source. While some outburst–to–outburst variations in the flux history are present, the SIGMA data indicate tentatively that the spectral evolution

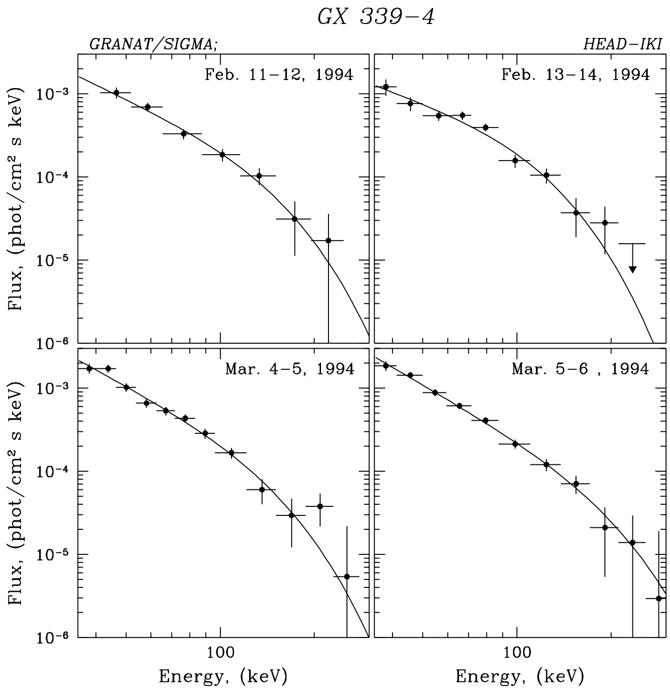

Fig. 3. The 40 – 300 keV spectra of GX 339-4 obtained by SIGMA in 1994. Solid lines represent the approximation of data with a comptonization model.

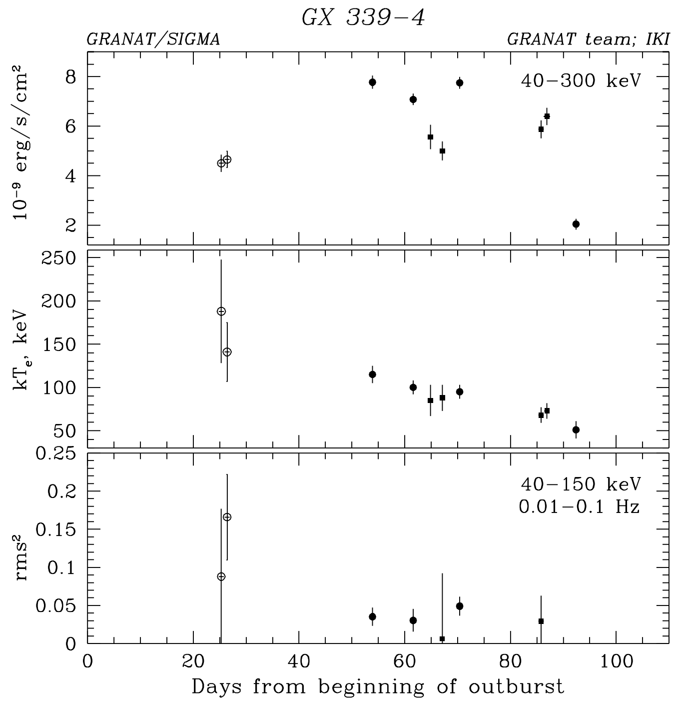

Fig. 4. The evolution of the characteristics of hard X-ray radiation from GX 339-4 with time since the beginning of the 1991, 1992 and 1994 outbursts: 40 – 300 keV energy flux – *upper panel* ; best–fit bremsstrahlung temperature – *middle panel* ; (0.01 – 0.1 Hz) fractional *rms*^{2} of 40 – 150 keV flux fluctuations – *lower panel*. Solid circles, open circles and solid squares in each pannel correspond to the 1991, 1992 and 1994 SIGMA data respectively. The start times of outbursts were taken from Harmon et al.1994*a*, Harmon et al.1994*b*.

during all three outbursts was quite similar and may be described as a gradual softening of the source high energy spectrum.

It is known from the hard X-ray observations of various black hole candidates (BHC) that the hardness of the high energy part of the spectrum is often related with the X-ray luminosity (e.g. Kuznetsov et al.1997, Revnivtsev et al.1996). In particular, the data acquired from observations of several X-ray Novae indicate, that the hardness of the spectrum is generally anti – correlated with mass accretion rate. Assuming, that the hard spectral component production mechanism in GX 339-4 is essentially the same we may tentatively suggest, that the gradual softening of the GX 339-4 spectrum during outburst corresponds to monotonic increase of the mass accretion rate.

Furthermore, comparing the simultaneous results of BATSE (Harmon et al.1994a) and ART – P and SIGMA (Grebenev et al.1993, Bouchet et al.1993) on the 1991 GX 339-4 outburst, we can conclude that the beginning of the *hard–to–soft* state transition coincided with the peak of the hard X-ray (≥ 20 keV) luminosity. On the other hand it was demonstrated that the soft spectral state corresponds to higher mass accretion rate than the hard state one (Trudolyubov et al.1996). Therefore, the peak of the mass accretion rate is reached well after the maximum of the hard X-ray luminosity – the observed decrease of the hard X-ray luminosity after it's maximum corresponds to the transition to soft spectral state and does not necessarily reflect decrease of the accretion rate.

According to the EXOSAT/ME (Ilovaisky et al.1986) and GINGA observations (Ueda et al.1994) the *off* state spectrum of GX 339-4 in the 2–20 keV band is extremely hard with the photon index ~ 1.7 (Fig. 5). This value is close to that for the hard (*low*) state (Grebenev et al.1993, Bouchet et al.1993, this paper), while the X-ray luminosity in off state is ~ 100 times lower than during the hard outburst. This is yet another example of surprisingly weak dependence of the slope ($\sim 2 - 20$ keV) of comptonized spectrum upon luminosity (e.g. Gilfanov et al. 1995).

4.2. Relation between spectral hardness and level of short–term variability

We have searched for possible correlation between short term fluctuations of the hard X-ray flux and the hardness of the source spectrum. The relation between the fractional rms (in the $10^{-2} - 10^{-1}$ Hz frequency range) of the $40 - 150$ keV flux fluctuations and best-fit bremsstrahlung temperature is shown in Fig. 6. It is seen from Fig. 6 that softening of the source spectrum is accompanied with decrease of the fractional rms. This behaviour resembles that of Cygnus X-1 (Kuznetsov et al.1997) and Nova Persei 1992 (GRO J0422+32) (Finoguenov et al.1996). This fact may hint on the general property of the hard spectral component production mechanism.

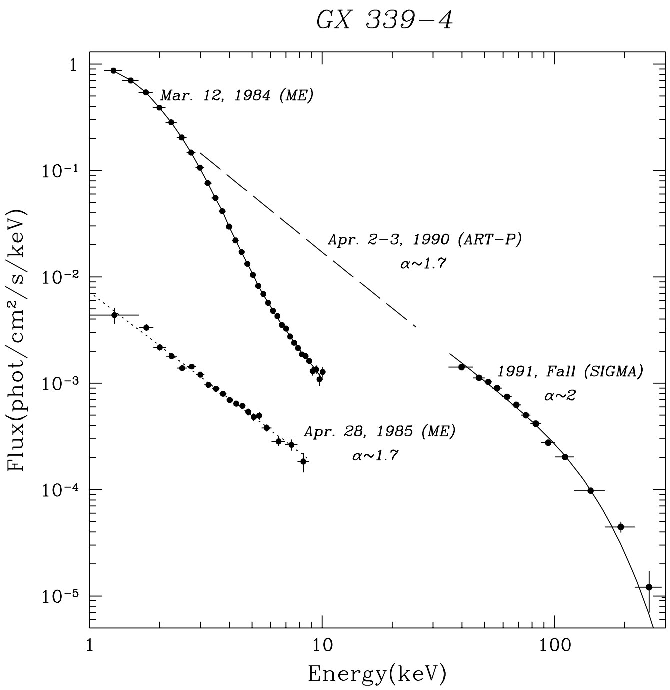

Fig. 5. Various spectral states of GX 339-4: *high(soft)* and *off* states-EXOSAT ME data; *low(hard)*– SIGMA and ART-P data (Grebenev et al.1993).

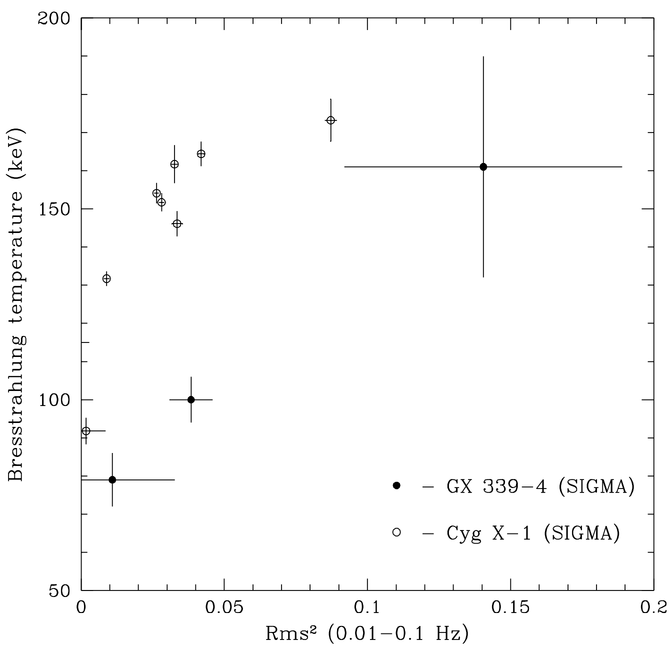

Fig. 6. The hardness of GX 339-4 hard X-ray (40 – 150 keV) spectrum in terms of best fit OTTB temperature vs. 10^{-2} – 10^{-1} Hz fractional *rms*^{2} variation. For comparison the Cyg X-1 results are shown (Kuznetsov et al.1997).

4.3. On the origin of the outbursts

Optical studies (Cowley, Crampton, & Hutchings 1987, Callanan et al.1992) identified GX 339-4 with a binary system containing a compact object with mass $1M_{\odot}\leq M_c \leq 2M_{\odot}$ and a probably evolved low mass secondary with luminosity $L_s\leq L_{\odot}$. In addition, the 14.8-hr binary period has been reported recently (Callanan et al.1992).

The BATSE observations have demonstrated that GX 339-4 hard X-ray ($\geq$20 keV) light curve during outburst is characterized by an initial rise of the flux during $\sim$ 1 month followed by slower increase up to the peak value during $\sim$2 months and relatively rapid drop within $\sim$20 days (Harmon et al.1993, Harmon et al.1994b). The evolution of the X-ray spectrum suggests that the maximum of the accretion rate is reached some time after the maximum of the hard X–ray luminosity, i.e. more than $\sim$ 3 month after the start of the outburst. This type of behavior is opposite to that of X-ray Novae during primary outbursts characterized by a short rise time ($\sim$ one week) and much slower decay of the X-ray luminosity on the timescale of months usually attributed to the disk instabilities.

Increase of the mass accretion rate onto compact object is thought to be the origin of the transient outbursts in the low mass X-ray binaries (LMXBs). Based upon the different mechanisms that explain this phenomena two competing models have been constructed. The mass transfer instability model (MTI; Hameury, King, & Lasota 1986, 1988, 1990) suggests that the outburst is caused by sudden increase of the mass transfer rate through the inner Lagrangian point (L_1) due to the expansion of the secondary's outer layers heated by hard X-rays generated in the vicinity of the compact object. The disk instability model (DTI; Lin & Taam 1984, Huang & Wheeler 1989, Mineshige & Wheeler 1989) attributes the outburst to the rising of the mass transfer rate through the accretion disk itself. Let us consider GX 339-4 state transitions in the framework of these models.

In the mass transfer instability model (MTI) the transient process is governed by the change of the mass transfer rate from a companion star on a timescale of its envelope expansion (Gontikakis & Hameury 1993) and by changing of mass transfer through the accretion disk on its diffusion timescale τ_{dif} $\sim$(r/v_r) $\sim$ ($1/\alpha\Omega$)(r/H)^2 $\sim$ several months (Lightman 1974) where *r* and *H* are the radius and the thickness of the disk, α and Ω are viscosity parameter and the Keplerian disk angular velocity (Shakura & Sunyaev 1973). On the other hand, the averaged measured pre-outburst GX 339-4 X-ray luminosity ($\geq 10^{35} D^2_{4kpc}$ ergs s^{-1}) (Ilovaisky et al.1986, Ueda et al.1994) is known to be higher than the required to initiate the expansion of the secondary's outer layers $\sim$ $10^{34} M_s^2$ ergs s^{-1} (Hameury, King, & Lasota 1986, Chen, Livio, & Gehrels 1993) where M_s is the secondary mass in the solar units. The disk thermal instability (DTI) has a characteristic timescale of order the disk heating wave propagation time τ_{heat} $\sim$ ($r/\alpha c_s$) $\sim$ ($1/\alpha\Omega$) (r/H) $\sim$ few days (Meyer 1984) where the c_s is the speed of sound. These facts and the absence of the fast rise in hard X-rays allow us to suppose the mass transfer instability (MTI) as an origin of the GX 339-4 hard state outbursts rather than the disk thermal instability (DTI).

Supposing that GX 339-4 outbursts are caused by the matter overflow through the inner Lagrangian point (L_1), let us define the degree of secondary Roche lobe (RL) overfill ΔR for a given system mass transfer rate. In the case of secondaries with sufficiently deep convective envelope the equation of state can be reasonably approximated by the polytropic law $p \propto \rho^{5/3}$, the relation between the mass transfer rate $\dot{M}$ the degree of RL overfill is follows: $\dot{M} \sim (M_s/P_B)(\Delta R/R_s)^3$ (Livio 1992, Lubow & Shu 1975) where M_s and R_s are the secondary mass and radius, P_B – is the binary period. The estimated hard state binary mass transfer is $\sim 3 \times 10^{-9}$ $(0.1/\eta)$ $M_\odot$ year^{-1}, where η is the efficiency of X-ray production, assuming the X-ray luminosity to be $\sim 2 \times 10^{37} (D/4$ kpc$)^2$ ergs s^{-1} (e.g. Grebenev et al.1993). Therefore, for the GX 339-4 hard state outbursts $\Delta R/R_s \sim 10^{-4}$, taking into account the uncertainty of the secondary mass determination. Can it be attributed to the intrinsic secondary radius fluctuations? It is known that in low mass binary systems, such as cataclysmic variables, long term secondary radius fluctuations exist, which is possibly linked to cycles in magnetic activity (Gontikakis & Hameury 1993). In addition, solar observations show $\Delta R/R_\odot \sim 10^{-4}$ within the solar cycle (Gilliland 1981). Although the possible influence of these fluctuations on the long term source behavior can not be completely excluded, their associated time scale (years) is too long to explain the observed transient events.

We propose that the sequence of the emission episodes during GX 339-4 outbursts is caused by the gradual increase of the mass transfer from the secondary onto the compact object due to the triggering of the irradiation-driven instability of the secondary outer layers. When the secondary outer layers expand to some extend, the mass transfer through the disk increases resulting in the *hard-to-soft* source state transition. X-ray illumination of the secondary is effective until thick accretion disk shields the L_1 region, quenching the instability (Hameury, King, & Lasota 1986). The following contraction of the unilluminated part of the secondary causes falling of the system mass transfer rate below critical value.

Proposed transient mechanism does not require the strict periodicity of the source outbursts. Furthermore, some destabilizing factors such as secondary intrinsic radius fluctuations discussed above, superimposed to the main instability cycle, may cause dramatic increase of the system mass transfer, resulting in the observed *super-high* state (Miyamoto et al.1991) or even be able to produce out of turn outbursts.

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